LBL--24175

DE88 004575

PERFORMANCE EVALUATION OF PEP*

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October 1987

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

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Abstract

An investigation of collective effects has been undertaken to assess the possibilities for using the low emittance operating mode of the PEP storage ring as a dedicated source of synchrotron radiation. Beam current limitations associated with longitudinal and transverse instabilities, and the expected emittance growth due to intrabeam scattering have been studied as a function of beam energy. Calculations of the beam lifetime due to Touschek and gas scattering are presented, and the growth times of coupled-bunch instabilities are estimated. In general, the results are encouraging, and no fundamental problems have been uncovered. It appears that beam currents up to about 10 mA per bunch should be achievable, and that the emittance growth is not a severe problem at an energy of about 8 GeV. A feedback system to deal with coupled-bunch instabilities is likely to be required.

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Introduction

In the recent past, it has become clear that synchrotron radiation is an important tool in many forms of scientific research. Although new storage rings dedicated to synchrotron radiation are now operating, and others are just beginning construction, there is still a significant need for a test bed for insertion devices, diagnostics, and experimental techniques that could be filled by dedicated use of the PEP storage ring—at some future date—to provide synchrotron radiation beams in the x-ray regime.

One could envision, for example, utilizing PEP to test specialized insertion devices destined for the 7 GeV Advanced Photon Source to be constructed at Argonne National Laboratory, or the European Synchrotron Radiation Project in Grenoble, France. To fulfill this role, of course, would likely require some changes in the PEP lattice, and would presumably require the machine to run at considerably lower energy than typically utilized for the existing PEP high energy physics programs.

In Ref. 1, a modified lattice was investigated that has an emittance of about one-quarter of the standard PEP collider optics. This solution is referred to here as the "Low Emittance Lattice" (LEL). In this paper, we examine the expected performance of the LEL in terms of electron beam collective effects. First, we explore the important issues of longitudinal and transverse single-bunch instabilities, which limit the allowable current and bunch length in the storage ring. Next, we assess the influence of intrabeam scattering on the beam emittance. Then, because of the requirements for reasonably high current and low emittance, we examine the issue of beam lifetime, which results from losses due both to large-angle Coulomb scattering (Touschek scattering) and to elastic and inelastic scattering from the background gas in the beam tube. Finally, we discuss the issue of coupled-bunch instabilities, which is likely to be relevant to the operation of PEP as a dedicated synchrotron radiation source.

Bunch Lengthening

In this section, we consider the effects of the longitudinal microwave instability (turbulent bunch lengthening) on the expected bunch length. The threshold current for the onset of this instability can be obtained from the characteristic value of the longitudinal impedance, $|Z/n|$, of the ring. To obtain the requisite value, we have analyzed with ZAP[2] existing low energy bunch length data (measured in the standard colliding beam lattice optics) taken at PEP.[3] The result, shown in Fig. 1, gives a value for $|Z/n|_0$ of 3 Ω. It is worth noting here that the calculation shown in Fig. 1 includes the expected impedance roll-off referred to as "SPEAR scaling" in Ref. 2. (We will see below that the value for $|Z/n|$ obtained in this manner is also roughly compatible with the value inferred from the observed transverse threshold.)

Having determined the value for the longitudinal impedance of

PEP, two example cases were investigated for the PEP LEL. For the first example, we consider the beam behavior at a very high RF voltage of 39 MV. This value typifies the situation where very short beam bunches are desired.[4] At the other extreme, we study the case of V_{RF} = 3 MV. This illustrates the situation where we want to have longer bunches to minimize the bunch density, and thus reduce any emittance blowup from intrabeam scattering. (In principle, we could select a somewhat different voltage for each energy, but for this illustration we have chosen a value that is compatible with beam energies up to about 8 GeV.) For both cases we fix the impedance value at $|Z/n| = 3\ \Omega$. In the case of the low RF voltage, of course, this assumption is pessimistic. (It has been estimated that about two-thirds of the ring impedance is due to the large number of RF cavities—most of which could be removed if only 3 MV were required.)

Results of bunch lengthening calculations at a beam current of 1 mA/bunch are shown in Figs. 2 and 3 for the 39 MV and 3 MV cases, respectively. For the high voltage case (Fig. 2) we expect bunch lengthening to be observed only below 6 GeV. At these low energies, the effect of intrabeam scattering (see below) would <u>also</u> cause some bunch lengthening, even if the turbulent bunch lengthening threshold were higher. Even with the expected bunch lengthening, however, an rms bunch length of less than 4 mm ($\sigma_\tau \approx$ 10 ps) is obtained.

In the low voltage case (Fig. 3), we see that significant bunch lengthening is expected, giving rms bunch lengths in the range of 2-3 cm ($\sigma_\tau \approx 80$ ps). The reason for the somewhat poorer behavior here, compared with that shown in Fig. 2, is that the longer bunches give rise to less roll-off of the effective longitudinal impedance, i.e., there is less benefit from the SPEAR scaling.

Transverse Limits

To determine the maximum permissible single-bunch current, we must examine the transverse thresholds. We again start from experimental results from Ref. 3, which indicate a threshold for the transverse mode-coupling instability[2,5] of about 1.5 mA. In ZAP, thresholds for both the transverse mode-coupling and transverse fast-blowup threshold instability are considered. Under the experimental conditions of Ref. 3, ZAP predicts a threshold for the fast blowup of $I_{FB} = 1.5$ mA and that for mode coupling to be slightly higher, $I_{MC} = 2$ mA. Thus, although the agreement is not perfect, we find that the transverse threshold is compatible with the longitudinal impedance value of $|Z/n| = 3\ \Omega$ determined from the bunch lengthening data.

Calculations for the two RF voltage assumptions are presented in Figs. 4 and 5. In the low voltage case, where the bunch lengths are in the same regime as that in the experiment,[3] we expect the transverse current limit to be below 5 mA/bunch. With the higher RF voltage, and the concomitant shorter bunches, the predicted threshold values are higher, but still limit the single-bunch current to below 10 mA at low energies. Given the fact that the calculations indicate bunch current limits in the range of interest, it will be worthwhile to investigate this matter in more detail than contained in ZAP.

Emittance Growth

At low beam energies (that is, energies well below the design energy for a particular storage ring), the natural emittance is generally small and the damping times are long. Thus, the beam density expected solely from synchrotron radiation effects is quite high, and we may have significant emittance growth due to small-angle, multiple Coulomb scattering of the particles within a beam bunch. This effect, referred to as intrabeam scattering (IBS), can be estimated with ZAP, which calculates the equilibrium emittance for a storage ring taking into account the growth term from IBS in addition to the effects of radiation damping and quantum excitation.

To be somewhat conservative, the calculations shown here were performed for the case of 1 mA/bunch, *but assuming no bunch lengthening*. This approach minimizes the longitudinal emittance and thus maximizes any transverse growth effects. Results for the 39 MV and 3 MV examples are shown in Figs. 6 and 7, respectively.

For the high voltage case (Fig. 6), we expect significant emittance growth only at energies below 4 GeV. At 2 GeV, for example, the equilibrium emittance including the effect of IBS is about 25 times larger than the natural emittance at that energy. Nonetheless, we can see that the equilibrium emittance value of 1.2 x 10^{-8} π m·rad is still quite low; indeed, this value is only about twice the value that would be obtained from the LBL 1-2 GeV Synchrotron Radiation Source[6] at this energy. At lower energies, however, the IBS emittance growth gets more and more severe. Thus, it would probably not be reasonable to contemplate running PEP at energies much below 2 GeV, even if the combined effects of the various beam instabilities—all of which become more severe at low energies—were to make this possible.

For the 3 MV case (Fig. 7), with its longer bunches, even less emittance growth is expected. In this case, only at 2 GeV do we expect significant growth. At the 2 GeV energy, we see that the equilibrium emittance is not improved very much compared with that shown in Fig. 6. Thus, reducing the RF voltage from 39 to 3 MV gives only a marginal improvement in the emittance growth.

Although not shown here, calculations have also been performed for the case of single-bunch currents of 1, 5 and 10 mA, but including the effects of bunch lengthening. For both RF voltage assumptions, the results look very similar to those shown in Figs. 6 and 7. This is because the additional longitudinal growth at higher currents is sufficient to keep the transverse emittance growth essentially the same.

Beam Lifetime

To estimate the beam lifetime, we must consider particle losses due to large-angle single Coulomb scattering within a beam bunch (Touschek scattering) and to both elastic and inelastic (bremsstrahlung) scattering from residual gas in the beam pipe (gas scattering). Each of these loss mechanisms is discussed below.

Touschek Scattering

The beam loss from Touschek scattering depends strongly on the momentum acceptance of the lattice, which can be limited either longitudinally (i.e., by the RF system acceptance) or transversely (i.e., by the physical or dynamic aperture). Both possibilities are considered with ZAP.[2]

In most lattices, the lifetime at low energies is determined by the transverse limits, because the RF acceptance at low energies is large. In the case of the PEP LEL, however, the lattice properties are rather ideal: the physical aperture is large and the dispersion is low. Thus, even for a very high RF voltage of 39 MV the momentum acceptance of the machine at energies above 4 GeV is limited by the RF system, leading to extremely large acceptance, and long Touschek lifetime. This is shown in Fig. 8, where the predicted lifetimes (under the same conditions as for Fig. 6) are in the range of 100 to 1000 hours at low energies. Because of the expected bunch lengthening at high currents, the lifetimes shown in Fig. 8 are nearly the same at a single-bunch current of 5 or 10 mA.

In contrast, for the low RF voltage of 3 MV, the longitudinal momentum acceptance is much lower, and is always the limiting acceptance. The resultant Touschek lifetimes, shown in Fig. 9, are much shorter than for the high voltage case (Fig. 8). Nonetheless, we will see below that gas scattering may still be the more serious concern.

It is also worth noting here that—as shown in the previous section—the reduction in transverse growth associated with the lower RF voltage (which gives longer, and thus less dense bunches) is not very substantial. Thus, the ability to improve the Touschek lifetime by increasing the RF voltage leads to little, if any, penalty.

Gas Scattering

Gas scattering lifetimes are calculated with ZAP including both elastic scattering and bremsstrahlung. For the elastic scattering, we must evaluate the betatron acceptance of the lattice. We take the limiting horizontal acceptance,

$$\mathcal{A}_x = \mathrm{Min}\ [b^2/\beta_x]$$

(where b is the aperture radius and the expression on the right hand side of the equation is evaluated as the minimum value anywhere in the lattice) directly from the lattice. We obtain a value of $\mathcal{A}_x = 8.4 \times 10^{-5}$ m, limited by the high-beta quadrupole.

For the limiting vertical acceptance, we make estimates in two different ways. First we consider the bare lattice, and evaluate the equivalent expression for the vertical acceptance from the lattice itself. Alternatively, we consider the extreme case of a 1-cm undulator gap located in the straight section (where $\beta_y = 100$ m). The former assumption gives $\mathcal{A}_y = 1.5 \times 10^{-5}$ m, limited in the arcs; the latter—obviously extreme—assumption, leads to $\mathcal{A}_y = 2.5 \times 10^{-7}$ m. (It is recognized, of course, that one would not, in reality, locate a small gap in a region of such a high beta function, so the lifetimes corresponding to this scenario should be viewed as a worst-case estimate.)

The bremsstrahlung acceptance, as for the Touschek lifetime discussed above, is usually limited by the RF acceptance, leading to a slight preference for the higher RF voltage. However, this cross section has a logarithmic dependence on the acceptance[2] and so does not change much as a function of either the RF voltage or the beam energy.

Predicted gas scattering lifetimes as a function of energy (assuming 1 nTorr of nitrogen gas) are shown in Fig. 10. In the situation where the vertical acceptance is limited by the undulator, the elastic scattering process limits the low energy lifetime to quite low values. Without the undulator, the lifetime is predicted to be dominated by bremsstrahlung, and thus stays essentially constant.

Combined Lifetimes

Overall lifetimes for the (worst-case) undulator scenario are given in Figs. 11 and 12 for the high and low RF voltage cases, respectively. In both cases, the lifetimes at low beam energies are very low, and might well be unacceptable for experiments.

In the "no undulator" case, where the aperture limit comes from the lattice physical aperture, the predicted lifetimes are much higher, as shown in Figs. 13 and 14 for the two RF assumptions. The message here is that the aperture at low energies should not be decreased too much below that for the normal lattice in order to maintain acceptable lifetimes.

Coupled-bunch Instabilities

If PEP were to be used as a dedicated source of synchrotron radiation, it is clear that it would need to be run in a multibunch mode. If we require, for example, a circulating beam current of about 100 mA, then the transverse beam current limitations, discussed earlier, imply at least a 10-bunch operating mode. For completeness, we have used ZAP to estimate coupled-bunch growth times for the case of 81 mA in 81 bunches (i.e., the same 1 mA/bunch assumption used elsewhere in this report). A selection of higher-order modes of the PEP RF cavities was obtained from similar calculations made for the SSC conceptual design.[7]

Especially for the high voltage case, the higher-order modes of the many RF cells will not simply add, since mechanical and temperature tolerances will cause frequency shifts among nominally identical cavities. To mock up this effect, the Q values of the cavity modes were decreased. In the longitudinal case, growth times on the order of 1 ms were obtained. As these times are considerably shorter than the radiation damping times at low energies, it is likely that a feedback system would be required. Transverse growth times are predicted to be somewhat longer, in the 5-10 ms range, but still are likely to require feedback for stabilization.

No attempt has been made as yet to explore the trade-offs associated with increasing the single-bunch current and decreasing the number of bunches. Such investigations should be made, of course, before making a final assessment of the need for, and parameters of, a feedback system.

Summary

In this report we have investigated the influence of various collective phenomena on the performance of PEP in its low emittance operating configuration. Comparison with experimental data on bunch lengthening gives an estimate for the longitudinal impedance of $|Z/n| = 3\ \Omega$. This value was utilized in the calculations reported here. With a high RF voltage of 39 MV, rms bunch lengths on the order of 10 ps should be achievable with a single-bunch current of 1 mA. Transverse beam current limitations are important, and estimates indicate that limiting single-bunch currents of about 10 mA can be reached. More detailed calculations should be performed to confirm this estimate.

The possibility of transverse emittance growth from intrabeam scattering at low energies has been studied. At energies above 2 GeV, this effect is not severe. An emittance growth of a factor of 25 beyond the natural emittance is expected at 2 GeV; growth at lower energies would become increasingly important.

Beam lifetimes due to Touschek and gas scattering have been estimated. The gas scattering process appears to dominate the predicted lifetime. As long as the vertical acceptance of the bare lattice is not severely degraded, acceptable lifetimes (a few hours) are expected if the background gas pressure is kept below 10 nTorr.

From preliminary calculations of both longitudinal and transverse coupled-bunch instability growth times, we find that they are significantly shorter than the lattice damping times at low energies. Thus, feedback systems are likely to be needed. More detailed calculations will be needed to confirm this result.

In conclusion, we have not uncovered any fundamental difficulties with the idea of using the PEP ring, in its low emittance mode, as a dedicated source of synchrotron radiation at beam energies near 8 GeV.

Acknowledgments

I would like to acknowledge many helpful discussions with Drs. S. Okuda, J.M. Paterson, L. Rivkin, and H. Winick (SLAC); Dr. A. Hofmann (CERN); and Dr. S. Chattopadhyay (LBL) in preparing this report.

<u>References</u>

1) G. Brown *et al.*, "Operation of PEP in a Low Emittance Mode," U.S. Particle Accelerator Conference, March, 1987, IEEE to be published.

2) M.S. Zisman, S. Chattopadhyay, and J.J. Bisognano, "ZAP User's Manual," Lawrence Berkeley Laboratory Report No. LBL-21270, December, 1986.

3) M. Donald *et al.*, "Feedback Experiment at PEP," CERN LEP Note 553, January, 1986.

4) A. Hofmann, "Short Bunches in PEP," Stanford Synchrotron Radiation Laboratory Report No. SSRL-ACD-39, November, 1986.

5) R. Ruth, "Single Bunch Instabilities in an SSC," in *Accelerator Physics Issues for a Superconducting Super Collider*, Ann Arbor, December, 1983, ed. M. Tigner, Univ. of Michigan Report No. UMHE 84-1, p. 151.

6) 1-2 GeV Synchrotron Radiation Source Conceptual Design Report, Lawrence Berkeley Laboratory Report No. PUB-5172 (Rev.), July, 1986.

7) Superconducting Super Collider Conceptual Design Report, SSC-SR-2020, March, 1986, p. 168.

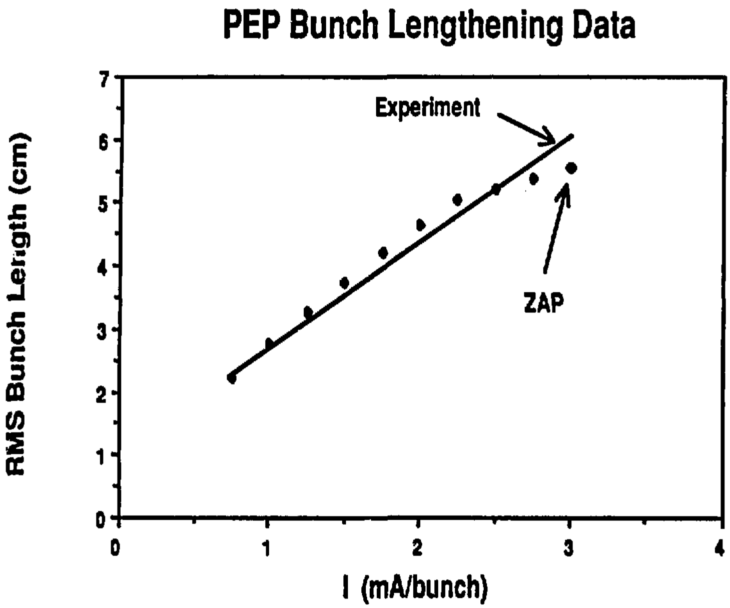

Fig. 1. Bunch lengthening results at 4.5 GeV. The solid line represents the experimental data; the points are ZAP calculations for $|Z/n| = 3\ \Omega$, assuming SPEAR scaling.

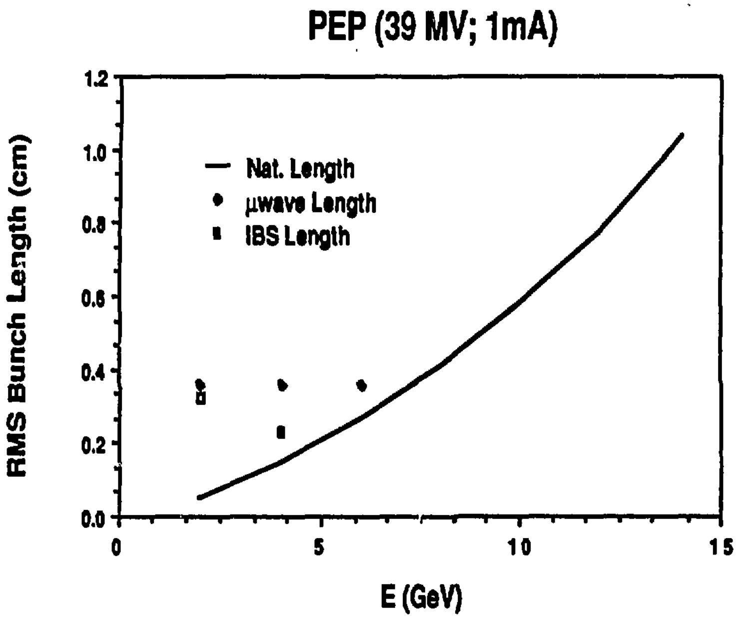

Fig. 2. Bunch length predictions for the PEP low emittance lattice with 1 mA/bunch. The line represents the natural bunch length with an RF voltage of 39 MV. The solid points include the effects of turbulent bunch lengthening. At low energies, intrabeam scattering would also lead to some bunch lengthening, as indicated by the open squares.

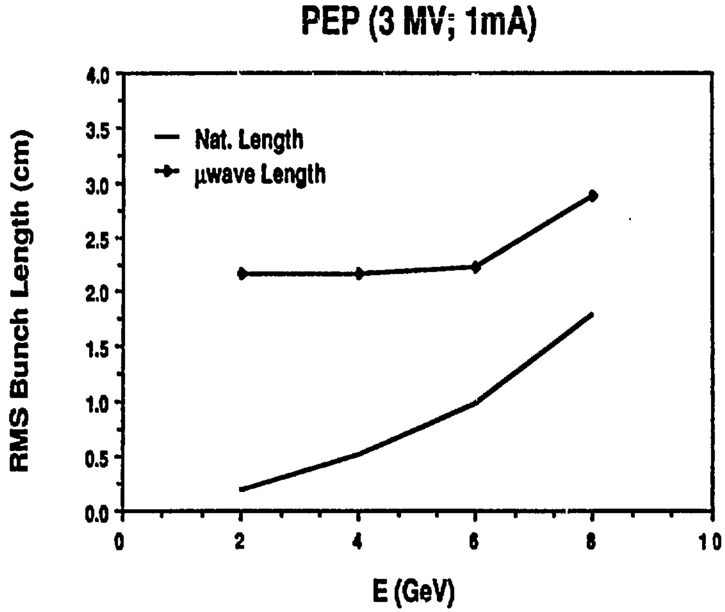

Fig. 3. Bunch length predictions for the PEP low emittance lattice with 1 mA/bunch. The line represents the natural bunch length with an RF voltage of 3 MV. The solid points include the effects of turbulent bunch lengthening.

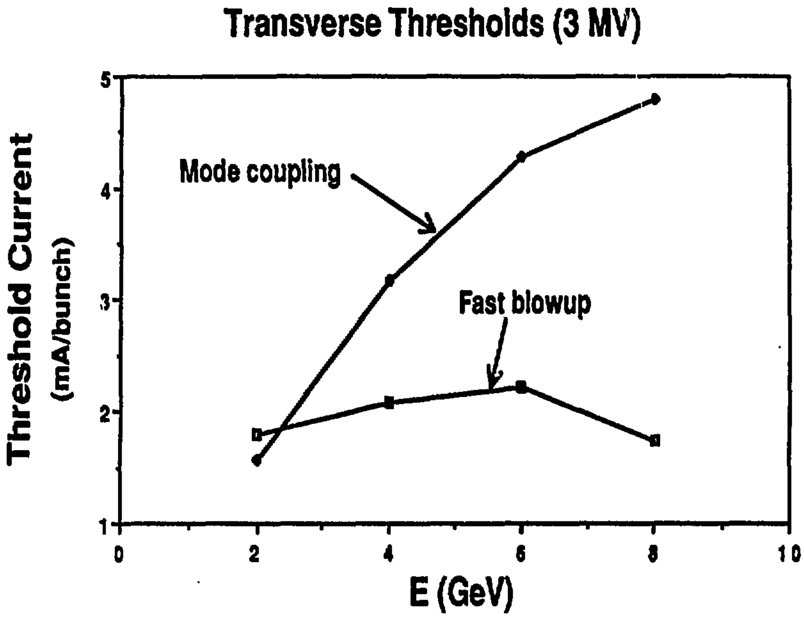

Fig. 4. Estimated thresholds for transverse fast blowup and transverse mode coupling instabilities, assuming an RF voltage of 3 MV.

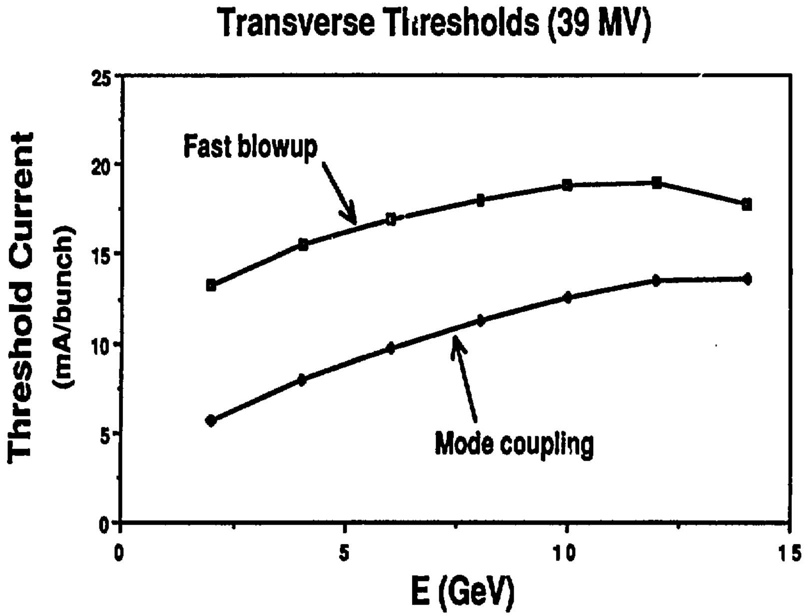

Fig. 5. Estimated thresholds for transverse fast blowup and transverse mode coupling instabilities, assuming an RF voltage of 39 MV.

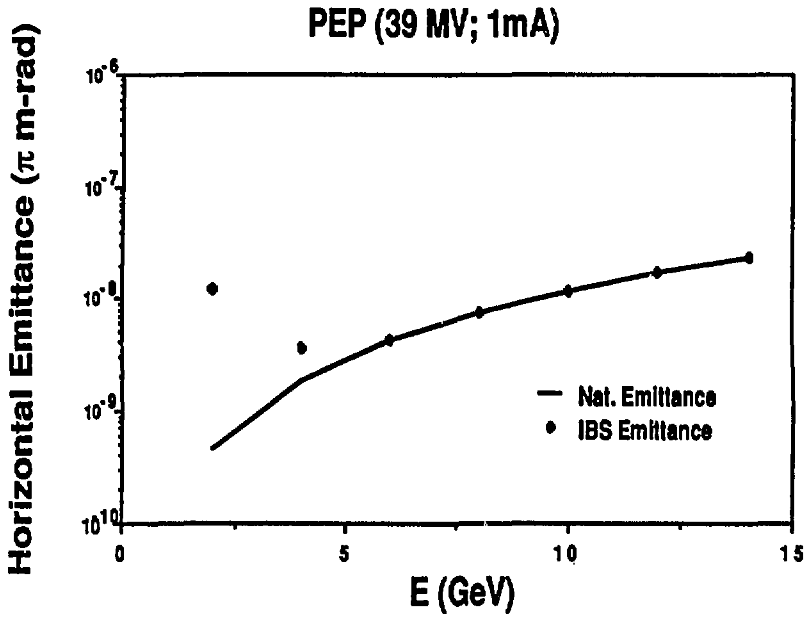

Fig. 6. Equilibrium horizontal emittance, including the effect of IBS, for a beam current of 1 mA/bunch and an RF voltage of 39 MV. Bunch lengthening effects were not included.

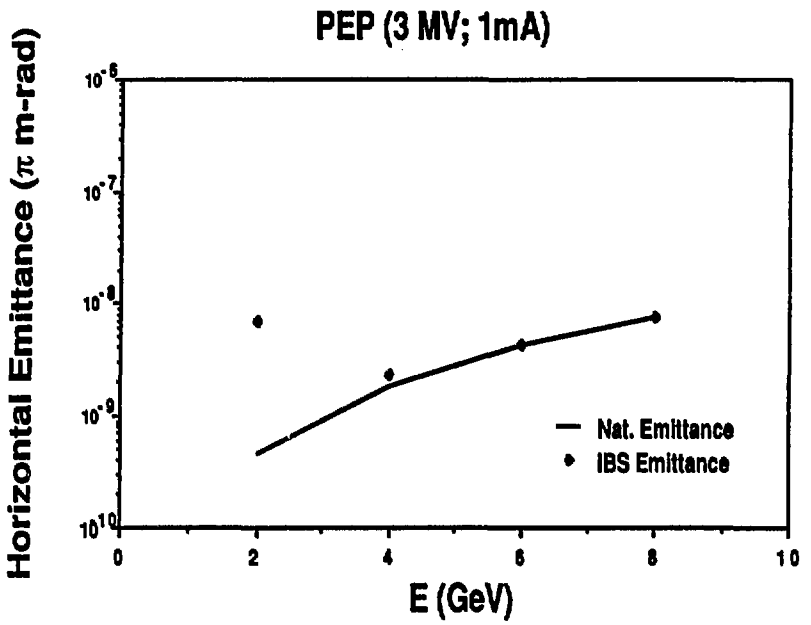

Fig. 7. Equilibrium horizontal emittance, including the effect of IBS for a beam current of 1 mA/bunch and an RF voltage of 3 MV. Bunch lengthening effects were not included.

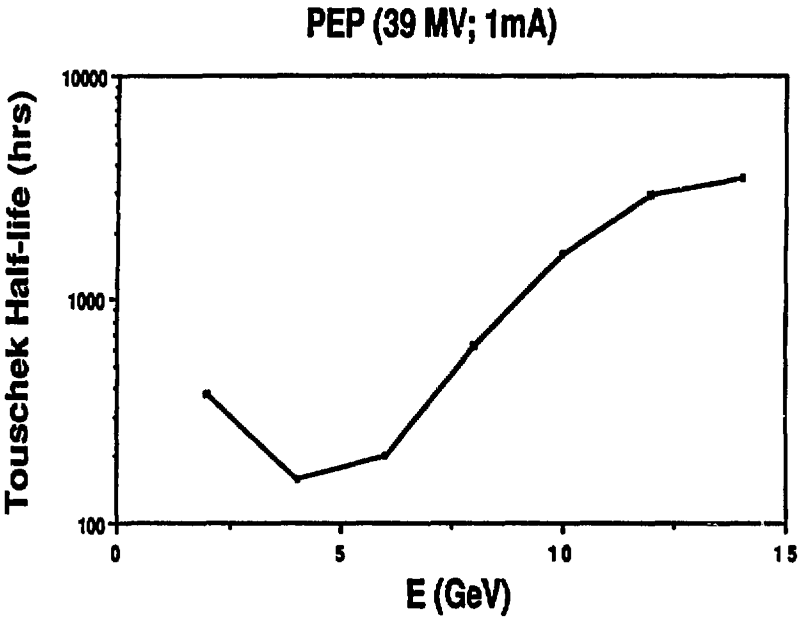

Fig. 8. Touschek lifetime for a beam current of 1 mA/bunch and an RF voltage of 39 MV. Bunch lengthening effects were not included.

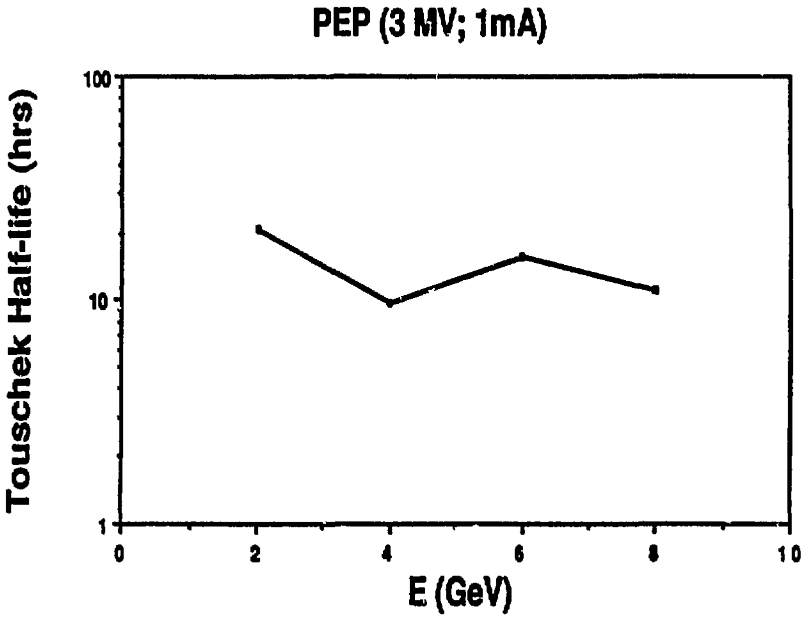

Fig. 9. Touschek lifetime for a beam current of 1 mA/bunch and an RF voltage of 3 MV. Bunch lengthening effects were not included.

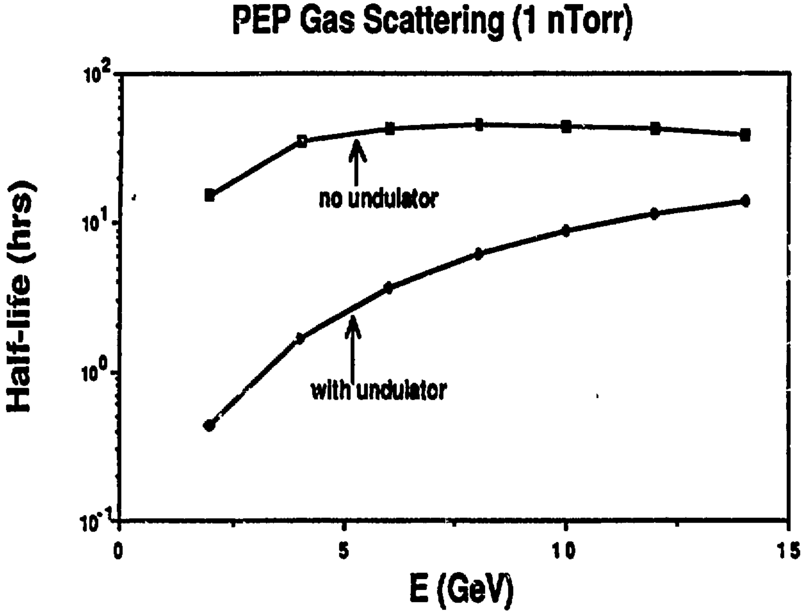

Fig. 10. Gas scattering lifetimes assuming 1 nTorr of nitrogen gas. The lower curve corresponds to a vertical limitation from a 1 cm undulator gap in the straight section; the upper curve represents the aperture limit of the standard lattice, and corresponds to a limit from the bending magnet gap in the arcs.

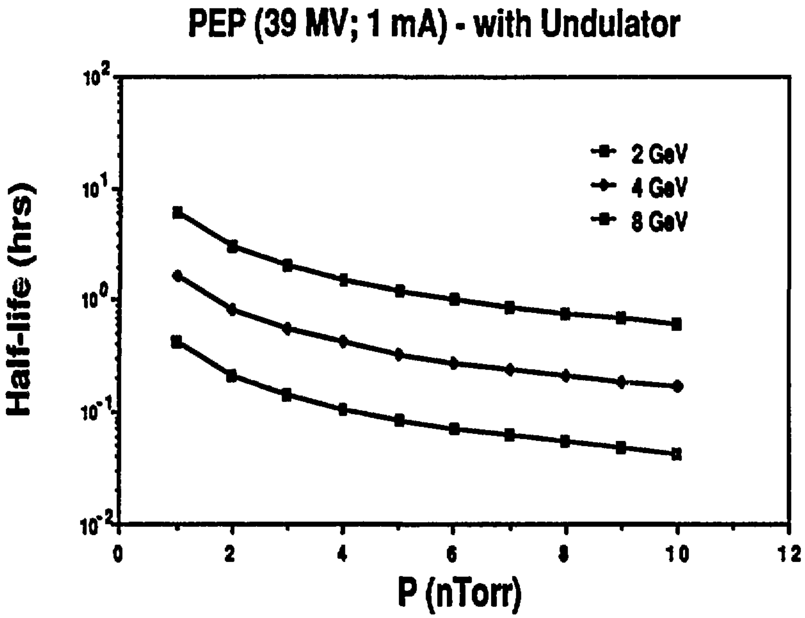

Fig. 11. Beam lifetime *vs.* pressure for the case of 1 mA/bunch and an RF voltage of 39 MV. The vertical aperture is limited by a 1 cm undulator gap in the straight section.

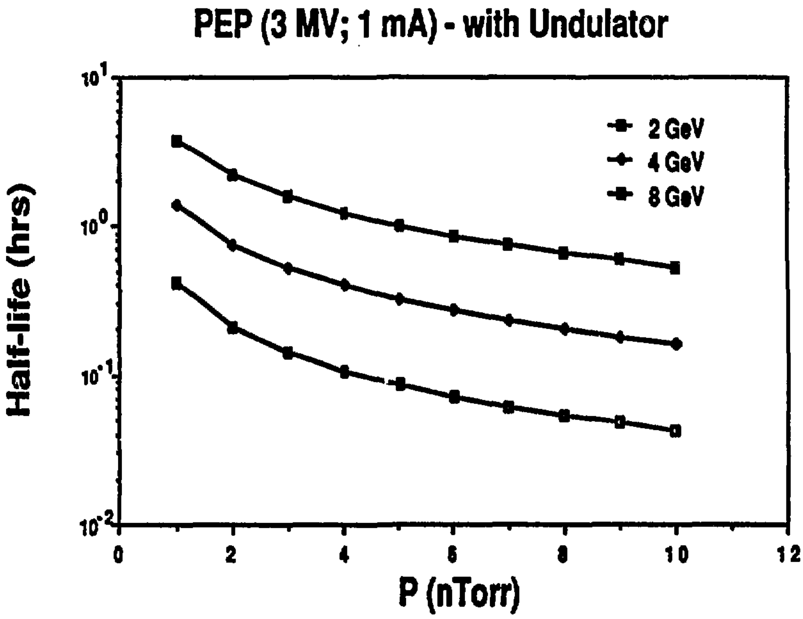

Fig. 12. Beam lifetime *vs.* pressure for the case of 1 mA/bunch and an RF voltage of 3 MV. The vertical aperture is limited by a 1 cm undulator gap in the straight section.

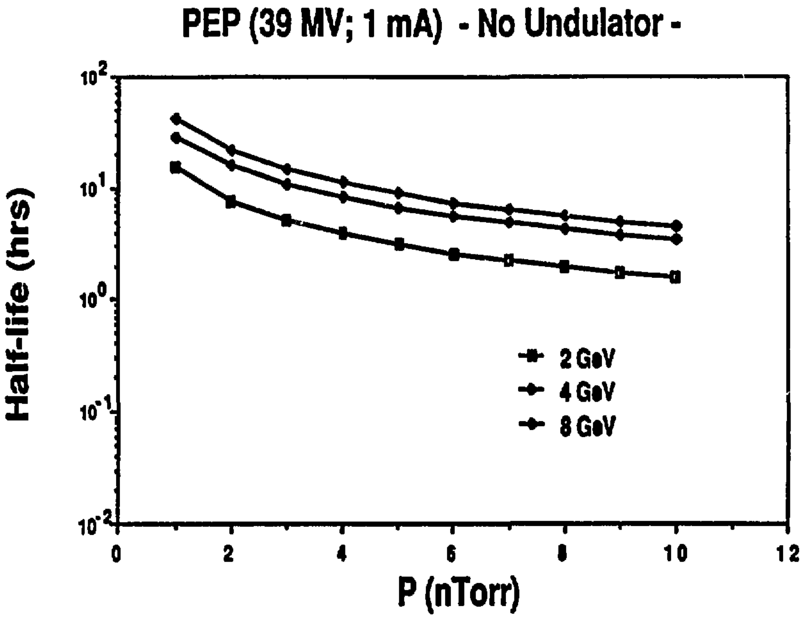

Fig. 13. Beam lifetime *vs.* pressure for the case of 1 mA/bunch and an RF voltage of 39 MV. The vertical aperture is limited by the magnet gap in the arcs.

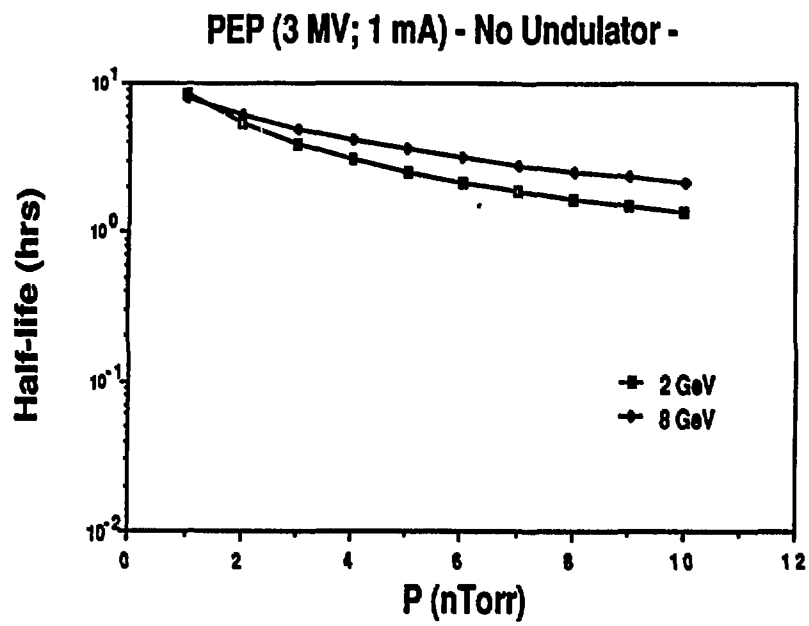

Fig. 14. Beam lifetime vs. pressure for the case of 1 mA/bunch and an RF voltage of 3 MV. The vertical aperture is limited by the magnet gap in the arcs.